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# 青藏高原南部拉萨地块中新世超钾质岩石中的锆石记录<sup>\*</sup>

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**Abstract** Zircons entrained in mantle-derived magmas offer a prime opportunity to reveal cryptic magmatic episodes in the deep crust. We have investigated zircons from mantle-derived ultrapotassic veins in the Xuena area, southern Lhasa subterrane. Zircons in the Xuena ultrapotassic rocks reveal four major magmatic pulses around <100Ma, 300 ~ 400Ma, 450 ~ 500Ma, and 700 ~ 850Ma. The high U/Yb ratios and low Y contents of these zircons demonstrate their continental origin. Cenozoic-Mesozoic and Late Paleozoic magmatism have been widely identified from the southern Lhasa subterrane, suggesting the contribution from overlying juvenile crust. But similar Proterozoic-Early Paleozoic age distributions (450 ~ 500Ma and 700 ~ 850Ma) between these zircon xenocrysts and those dating records in the Himalayan orogenic belt corroborate the input from underthrust Indian continental crust. Furthermore, the increasing (Dy/Yb)<sub>N</sub> ratio since ~60Ma and rapid decreasing zircon  $\varepsilon_{\text{Hf}}(t)$  values, from +10 ~ +5 to -10 ~ -25, are interpreted to reflect significant and progressive crustal thickening in response to India-Asia convergence and the contribution from subducted Indian continental crust to postcollisional magmatism in the southern Lhasa sub-terrane.

**Key words** Zircon; Ultrapotassic vein; U-Pb dating; Hf isotope; Xuena area; Lhasa Terrane; Tibet Plateau

**摘 要** 幔源岩浆上升的过程中捕获的锆石为揭示深部地壳“隐藏”的岩浆作用事件提供了宝贵机会。本文对采自南部拉萨地块学那地区的超钾质脉岩中的锆石进行了 U-Pb 年代学、微量元素和 Hf 同位素研究。研究结果表明,学那超钾质岩石中的锆石主要展示出 4 个主要的年龄峰值,分别是: <100Ma、300 ~ 400Ma、450 ~ 500Ma 以及 700 ~ 850Ma。这些锆石高 U/Yb 比值、低 Y 含量的特征暗示起源于大陆地壳。而新生代-中生代(<100Ma)和晚古生代(300 ~ 400Ma)的岩浆活动在南部拉萨地块上广泛发育,这表明南部拉萨地块新生地壳物质对学那超钾质岩浆活动的贡献。但是超钾质脉岩中早古生代和元古代(450 ~ 500Ma 和 700 ~ 850Ma)锆石捕掳晶的存在则证实印度大陆

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地壳物质的加入。此外,从大约 55 Ma 左右开始,锆石颗粒的  $(\text{Dy}/\text{Yb})_{\text{N}}$  比值开始逐渐增高,  $\varepsilon_{\text{Hf}}(t)$  值则从  $+10 \sim +5$  迅速下降至  $-10 \sim -25$ 。考虑到南部拉萨地块新生地壳的同位素组成特征,超钾质脉岩中的这些锆石颗粒可能记录了印度-亚洲陆陆汇聚过程中地壳的显著加厚以及俯冲的印度大陆地壳物质对南部拉萨地块后碰撞岩浆作用的贡献。

**关键词** 锆石;超钾质脉岩;U-Pb 定年;Hf 同位素;学那地区;拉萨地块;青藏高原

**中图法分类号** P588.13; P597.3

拉萨地块中新世的超钾质岩浆活动广受关注,尤其是这类岩石的成因一直存在多种解释(Turner *et al.*, 1996; Miller *et al.*, 1999; Ding *et al.*, 2003; Nomade *et al.*, 2004; 赵志丹等, 2006; Zhao *et al.*, 2009; 刘栋等, 2011)。这种幔源富钾岩浆明显富集的同位素组成被认为是俯冲的印度大陆地壳物质对地幔源区交代富集的结果(赵志丹等, 2006; Zhao *et al.*, 2009),或者代表着陆陆碰撞之前洋壳俯冲过程中沉积物的交代作用(Gao *et al.*, 2009; Tommasini *et al.*, 2010; Liu *et al.*, 2013b)。然而近年来拉萨地块自身的地壳物质加入到超钾质岩浆中的过程愈发不可忽视,主要表现在:一是最近的研究结果表明拉萨地块的核部存在成熟的古老地壳基底(Zhu *et al.*, 2011a),并且拉萨地块和印度大陆可能都是东冈瓦纳大陆裂解的产物(Zhu *et al.*, 2011b, 2013);二是在拉萨地块超钾质岩石中存在地壳物质混染的岩石学和地球化学证据,包括岩石具有低  $\text{CaO}/\text{Al}_2\text{O}_3$  比值,上凸的 Sr-O 同位素混合趋势,与拉萨地块一致的 Pb 同位素组成,以及广泛存在的地壳包体等(Hébert *et al.*, 2013; Liu *et al.*, 2013a, b)。因此在这种碰撞后幔源岩浆的演化过程中存在拉萨地块本身的地壳物质加入导致岩浆发生富集作用的可能。由于拉萨地块本身的地壳物质和俯冲到拉萨地块之下的印度大陆地壳的物质在地球化学性质上具有一定相似性(Liu *et al.*, 2013b),尤其是在拉萨地块的中部,从超钾质岩石中识别出上述两者的贡献比例是比较困难的。但是在以新生地壳为主要特征的南部拉萨地块(Ji *et al.*, 2009; Zhu *et al.*, 2011a),利用超钾质岩石来示踪印度大陆的俯冲显得更为有效。

锆石作为物理性质稳定,并且兼有定年和地球化学示踪功能的重要工具,近年来已经发挥了重要的作用(Hoskin and Schaltegger, 2003)。先前的研究发现在中部拉萨地块的幔源超钾质火山岩存在大量不同年龄的锆石捕虏晶,为岩石成因与演化过程提供了重要信息(孙晨光等, 2008; Liu *et al.*, 2013a)。本文对采自于南部拉萨地块学那地区的超钾质脉岩进行了详细的野外观察和采样,也获得了具有从元古代到中新世 U-Pb 年龄的锆石捕虏晶。其中,具有中-新生代年龄的锆石为反演南部拉萨地块地壳演化提供了新的视角;而古生代-元古代古老锆石的发现则为进一步阐明超钾质岩浆的起源提供了新的制约。

## 1 地质背景和样品

拉萨地块分别以雅鲁藏布缝合带(IYZS)和班公湖怒江缝合带(BNS)为南北界线,并被狮泉河-纳木错蛇绿混杂岩带(SNMZ)和洛巴堆-米拉山断裂(LMF)进一步分为北部拉萨地块、中部拉萨地块和南部拉萨地块三个构造单元(图 1a, Zhu *et al.*, 2011a)。后碰撞超钾质岩浆活动主要产出于中部拉萨地块。大部分超钾质火山岩以呈熔岩形式产出,不整合覆盖于中-新生代的火山-沉积地层之上(Turner *et al.*, 1996; Miller *et al.*, 1999; Nomade *et al.*, 2004; 刘栋等, 2011; Zhao *et al.*, 2009; Liu *et al.*, 2013b)。仅有少量超钾质岩石以脉岩的形式侵位于南部拉萨地块的沉积底层之中(Williams *et al.*, 2001; Chan *et al.*, 2009)。本文研究区位于南部拉萨地块中段的学那地区(图 1a)。在研究区内,超钾质岩脉侵位于日喀则复理石沉积地层中(图 1b, c)。所采超钾质岩石为灰色-灰黑色的地幔云母岩,斑晶矿物主要为呈片状产出的金云母(图 2a),含量在 20% 左右(最高可达 30%);其次含少量单斜辉石和斜方辉石,呈粒状产出(图 2b)。

## 2 分析方法

选取新鲜的云母岩样品破碎至 80 目,经过磁选、重液分选和双目镜下手工挑选等方法挑选出锆石,并将挑选出的锆石粘贴制成环氧树脂样品靶,打磨使其露出内部。之后对其进行透射光、反射光和阴极发光(CL)显微照相。锆石 U-Pb 同位素定年在中国地质大学(武汉)地质过程与矿产资源国家重点实验室利用 LA-ICPMS 分析完成的。激光剥蚀系统为 GeoLas 2005,电感耦合等离子质谱(ICP-MS)为 Agilent 7700x。在等离子体中心气流( $\text{Ar} + \text{He}$ )中加入少量氮气以提高仪器灵敏度、降低检出限和改善分析精密性(Hu *et al.*, 2008)。激光斑束直径为  $32\mu\text{m}$ 。详细的仪器操作条件和数据处理方法见 Liu *et al.* (2008; 2010)。定年过程中采用 91500 作为内标校正同位素分馏,每隔 6 个数据点分别用两个 91500 标样校正。锆石微量元素含量利用多个 USGS 参考玻璃(BCR-2G, BIR-1G)作为多外标、 $\text{Si}^{29}$  作为内标进行定量校正。对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及 U-Th-Pb 同位素比值和年龄计算均采用软件 ICPMSDataCal9.0 进行离线处理(Liu *et al.*, 2008, 2010)。采

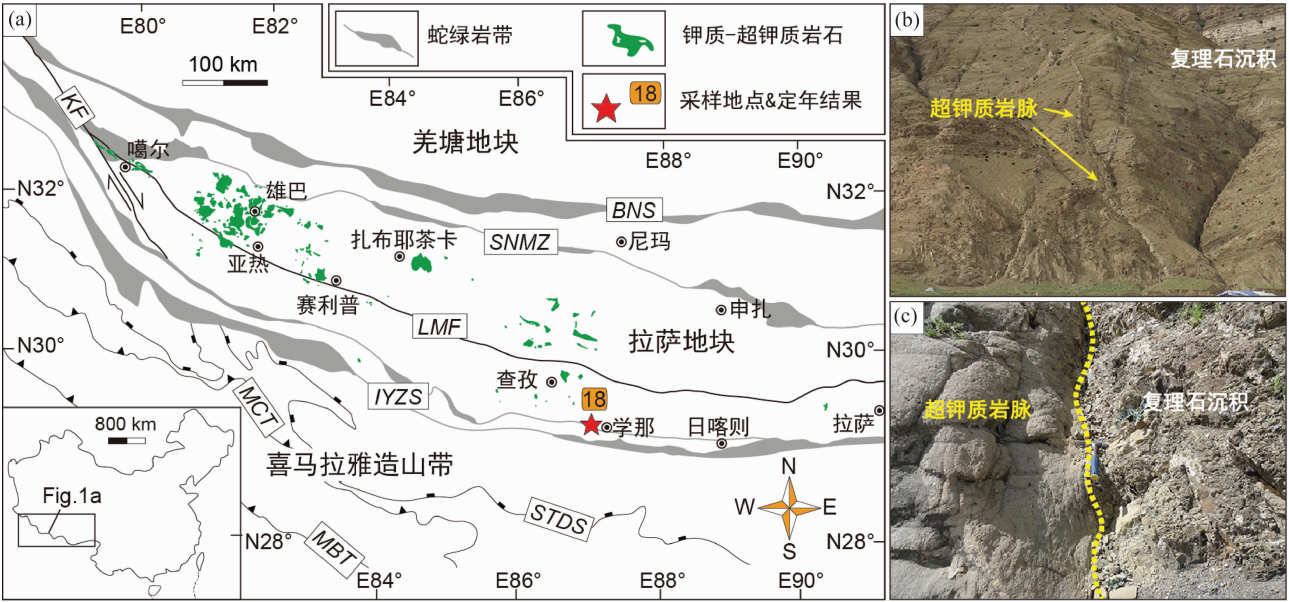


图 1 藏南后碰撞钾质-超钾质岩浆时空分布图(a,据 Liu *et al.* , 2013a 修改)、学那地区超钾质岩脉露头野外照片(b)和超钾质脉岩与围岩接触关系野外照片(c)

BNS = 班公湖-怒江缝合带; SNMZ = 狮泉河-纳木错蛇绿混杂岩带; LMF = 洛巴堆-米拉山断裂; IYZS = 印度-雅鲁藏布缝合带; STDS = 藏南拆离系; MCT = 主中央断层; MBT = 主边界断层

Fig.1 Geological map for the spatial distribution of post-collisional potassic-ultrapotassic magmatism in southern Tibet (a, modified after Liu *et al.* , 2013a), the field photograph for the outcrop of ultrapotassic veins in Xuena area (b) and the contact relationship between ultrapotassic vein and wallrock (c)

BNS = Bangong-Nujiang Suture zone; SNMZ = Shiquan River-Nam Tso Ophiolitic Melange Zone; LMF = Luobadui-Mila Mountain Fault; IYZS = Indus-Yarlung Zangbo Suture zone; STDS = Southern Tibetan Detachment System; MCT = Main Central Thrust; MBT = Main Boundary Thrust

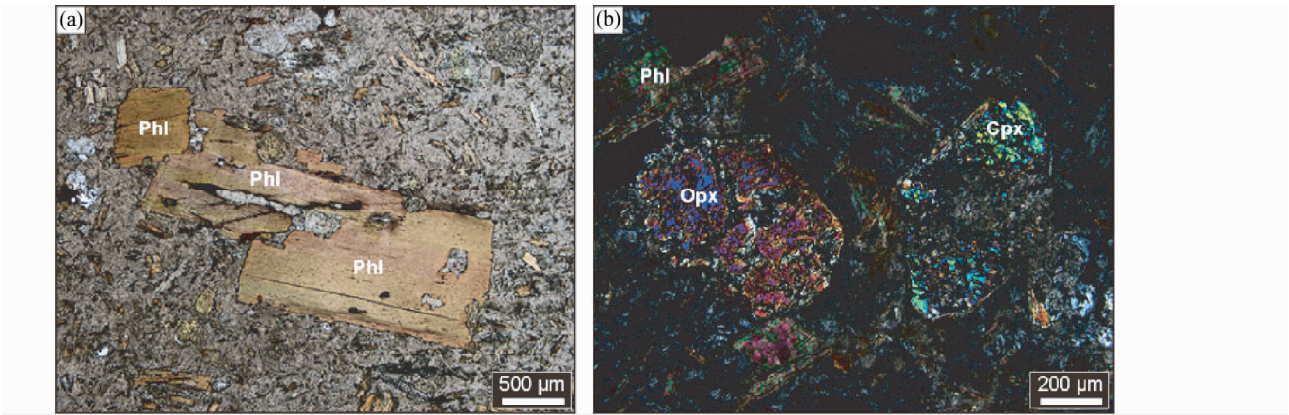


图 2 藏南学那地区幔源超钾质云母岩矿物显微照相  
Cpx-单斜辉石; Opx-斜方辉石; Phl-金云母

Fig.2 Microphotographs for mantle-derived ultrapotassic glimmerite in the Xuena area, southern Tibet  
Cpx-clinopyroxene; Opx-orthopyroxene; Phl-phlogopite

用 Andersen (2002) 进行普通铅校正, 锆石 U-Pb 年龄谱和图的绘制和 MSWD 的计算则采用 Isoplot/Ex\_ver3 (Ludwig, 2003)。锆石定年和微量元素分析结果见图 3 和表 1、表 2、表 3。

锆石 Hf 同位素分析是在中国地质大学 (武汉) 地质过程与矿产资源国家重点实验室采用 LA-MC-ICPMS (Neptune

Plus) 完成的。激光剥蚀系统为 GeoLas 2005 (Lambda Physik, Göttingen, Germany)。激光斑束直径为 44  $\mu\text{m}$ 。采用 91500 锆石标样进行仪器状态监测。详细的仪器操作条件和数据处理方法见 Hu *et al.* (2012)。离线数据处理和质量漂移校正采用 ICPMSDataCal9.0 (Liu *et al.* , 2010)。



表 1 藏南后碰撞超钾质脉岩定年结果

Table 1 Dating results for post-collisional ultapotassic veins in southern Tibet

样品号	地名	岩性	地球化学特征	定年方法	年龄结果(2σ)	数据来源
XN1207	学那		SiO <sub>2</sub> = 56.1wt%、K <sub>2</sub> O = 5.7wt%、 K <sub>2</sub> O/Na <sub>2</sub> O = 2.1	Zircon U-Pb	18.0 ± 0.7Ma	本文
158g 158p	学那	超钾质地 幔云母岩	SiO <sub>2</sub> = 56.1wt%、K <sub>2</sub> O = 5.7wt%、 K <sub>2</sub> O/Na <sub>2</sub> O = 7.7	Zircon U-Pb	16.8 ± 0.9Ma 15.6 ± 0.6Ma	Chan <i>et al.</i> , 2009
JP17 T5A	Pabbai zong		SiO <sub>2</sub> = 57.0wt%、K <sub>2</sub> O = 5.0wt%、 K <sub>2</sub> O/Na <sub>2</sub> O = 2.5	Phlogopite <sup>40</sup> Ar- <sup>39</sup> Ar	18.3 ± 2.7Ma 13.3 ± 0.4Ma	Williams <i>et al.</i> , 2001

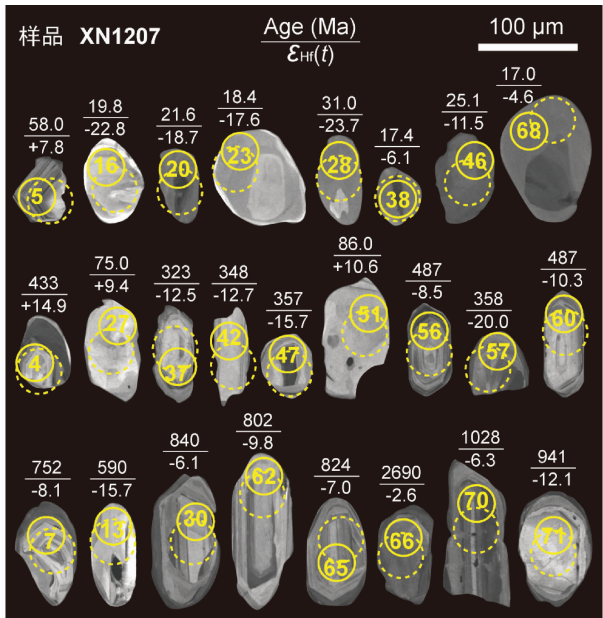


图 3 藏南学那地区超钾质脉岩锆石 CL 图像  
其中实线圆圈和虚线圆圈分别代表 U-Pb 激光束斑位置(直径 32μm)和 Hf 同位素激光剥蚀位置(直径 44μm)  
Fig. 3 CL images for zircons from ultrapotassic veins outcropped in the Xuena area, southern Tibet  
The solid and dashed circles refer to the locations of the laser ablation for zircon U-Pb analyses (diameter = 32μm) and zircon Hf isotopes analyses (diameter = 44μm), respectively

3 分析结果

3.1 锆石 U-Pb 定年和微量元素

对超钾质云母岩(XN1207)锆石的定年结果表明,其年龄显示出从 2690Ma 到 17Ma 的大范围变化(图 4a),形成了 <100Ma, 300~400Ma, 450~500Ma 以及 700~850Ma 四个明显的年龄峰值(图 4b)。在剔除不谐和的年龄之后,获得最年轻的中新世锆石的<sup>206</sup>Pb/<sup>238</sup>U 加权平均年龄值为 18.0 ± 0.7Ma (2σ, n=4, MSWD = 2.29, 图 4a),该结果在区域上与南部拉萨地块超钾质脉岩的早中新世的 Ar-Ar 定年结果相近(表 1, Williams *et al.*, 2001; Chan *et al.*, 2009)。在阴

极发光(CL)图像上(图 3),地幔云母岩的新生代锆石颗粒粒径较小(≤ 100μm),大多被熔蚀成圆状-次圆状,具有弱或无同心震荡环带;而古生代-中生代的锆石捕虏晶大多呈长条状(长宽比为 2:1~3:1),具有比较明显的生长环带;元古代-太古代的古老锆石通常具有较大的粒径并且呈现出复杂的内部结构,发育核边结构。尽管在形态和内部结构上有差异,云母岩中的锆石大都呈现出高的 Th、U 含量和 Th/U 比值(表 2)、Ce 正异常、Eu 负异常以及 HREE 相对富集的稀土配分模式(图 4c),表明这些锆石仍具有典型岩浆锆石特征(Hoskin and Schaltegger, 2003)。此外,少量石炭纪和新生代的锆石捕虏晶的 Th/U 比值低于 0.07(图 5a),表明这部分锆石可能形成于变质过程中。

3.2 锆石 Hf 同位素

对样品中 65 颗具有谐和年龄的锆石进行了 Hf 同位素分析,其<sup>176</sup>Yb/<sup>177</sup>Hf 和<sup>176</sup>Lu/<sup>177</sup>Hf 变化范围分别为 0.002007~0.149811 和 0.000058~0.004277(表 4),表明锆石形成之后积累的放射性成因 Hf 同位素很少,<sup>176</sup>Hf/<sup>177</sup>Hf(t) 可以代表锆石形成时的 Hf 同位素比值。锆石 ε<sub>Hf</sub>(t) 值的变化范围为 -45.8~+14.9,相应的 Hf 同位素亏损地幔模式年龄和地壳模式年龄分别为 t<sub>DM</sub> = 3094~308Ma 和 t<sub>DM</sub><sup>C</sup> = 4159~443Ma(图 4d、表 4)。

4 讨论

4.1 超钾质脉岩锆石起源与印度大陆俯冲

尽管学那中新世超钾质脉岩出露于日喀则复理石沉积中(图 1b, c),但是与日喀则弧前沉积的碎屑锆石主要以~55Ma 和~180Ma 为特征年龄峰值的分布趋势不同(Wu *et al.*, 2010),超钾质脉岩的锆石记录完全缺少~180Ma 的年龄记录(图 4b)。加上锆石颗粒较差的磨圆度(图 3),暗示这些锆石可能并非超钾质岩浆从沉积围岩中捕获,而是来自南部拉萨地块的深部地壳。学那超钾质脉岩中的锆石具有高的 U/Yb 比值和相对低的 Y 含量,完全落入大陆地壳锆石的成分范围内(图 5b),这表明这些锆石起源于大陆地壳。因此南部拉萨地块的新生地壳和俯冲的印度大陆地壳都可能作为这些锆石的源区。

表 2 藏南学那地区超钾质岩石锆石 U-Pb 年龄数据

Table 2 U-Pb age data of zircons from ultrapotassic rocks in Xuena area, southern Tibet

测点号	含量( × 10 <sup>-6</sup> )			Th/U	同位素比值						年龄(Ma)								
	Pb	Th	U		<sup>207</sup> Pb/ <sup>206</sup> Pb		1σ	<sup>207</sup> Pb/ <sup>235</sup> U		1σ	<sup>206</sup> Pb/ <sup>238</sup> U		1σ	<sup>207</sup> Pb/ <sup>235</sup> U		1σ	<sup>206</sup> Pb/ <sup>238</sup> U		1σ
XN1207-01	124.98	1674.3	4244.8	0.39	0.0476	0.0022	0.0660	0.0032	0.0100	0.0001	81	83	65	3	64	1			
XN1207-02	82.46	1073.5	3158.4	0.34	0.0474	0.0026	0.0588	0.0032	0.0090	0.0001	70	91	58	3	58	1			
XN1207-03	342.60	299.9	897.2	0.33	0.0850	0.0028	1.6315	0.0618	0.1397	0.0030	1315	41	982	24	843	17			
XN1207-04	315.19	400.8	2949.6	0.14	0.0549	0.0017	0.5273	0.0167	0.0695	0.0010	408	46	430	11	433	6			
XN1207-05	93.87	1534.4	2479.8	0.62	0.0474	0.0033	0.0587	0.0043	0.0090	0.0002	70	123	58	4	58	1			
XN1207-06	34.97	95.4	98.8	0.97	0.0849	0.0069	0.6305	0.0512	0.0573	0.0020	1313	103	496	32	359	12			
XN1207-07	317.84	229.9	1699.2	0.14	0.0668	0.0019	1.1394	0.0302	0.1237	0.0011	831	60	772	14	752	6			
XN1207-08	476.93	776.7	1071.3	0.72	0.0649	0.0017	1.0353	0.0274	0.1159	0.0017	770	32	722	14	707	10			
XN1207-09	17.53	75.3	3230.0	0.02	0.0488	0.0027	0.0439	0.0028	0.0066	0.0002	139	91	44	3	43	1			
XN1207-10	231.26	34.4	6087.7	0.01	0.0562	0.0015	0.3938	0.0092	0.0508	0.0006	461	59	337	7	319	4			
XN1207-11	250.21	157.4	2942.4	0.05	0.0657	0.0021	0.4839	0.0162	0.0533	0.0006	796	50	401	11	335	4			
XN1207-12	82.90	155.2	304.0	0.51	0.0633	0.0036	0.5885	0.0323	0.0708	0.0019	717	72	470	21	441	11			
XN1207-13	147.93	193.1	595.5	0.32	0.0615	0.0024	0.8071	0.0312	0.0958	0.0017	656	52	601	18	590	10			
XN1207-14	30.68	28.1	3570.7	0.01	0.0466	0.0026	0.0768	0.0035	0.0120	0.0004	27	121	75	3	77	2			
XN1207-15	128.64	2049.6	2192.1	0.93	0.0461	0.0056	0.0572	0.0069	0.0090	0.0002		239	56	7	58	1			
XN1207-16	2.40	18.4	1132.1	0.02	0.0533	0.0062	0.0197	0.0009	0.0031	0.0001	341	48	20	1	20	1			
XN1207-17	340.16	274.5	537.6	0.51	0.0824	0.0034	2.2928	0.0897	0.2018	0.0023	1256	82	1210	28	1185	13			
XN1207-18	271.56	417.1	624.2	0.67	0.0694	0.0023	1.1727	0.0377	0.1227	0.0015	910	46	788	18	746	9			
XN1207-19	106.16	19.1	2652.1	0.01	0.0537	0.0023	0.3174	0.0129	0.0429	0.0006	357	100	280	10	271	4			
XN1207-20	12.16	42.6	5079.3	0.01	0.0470	0.0048	0.0216	0.0020	0.0034	0.0001	50	157	22	2	22	1			
XN1207-21	395.52	491.3	2826.5	0.17	0.0709	0.0016	1.0062	0.0255	0.1024	0.0015	955	29	707	13	628	9			
XN1207-22	101.16	28.6	2470.8	0.01	0.0669	0.0022	0.4177	0.0127	0.0453	0.0005	834	68	354	9	286	3			
XN1207-23	4.58	57.1	1281.1	0.04	0.0491	0.0062	0.0182	0.0021	0.0029	0.0001	151	196	18	2	18	1			
XN1207-24	602.42	1679.0	1897.9	0.88	0.0565	0.0018	0.5744	0.0177	0.0740	0.0010	470	44	461	11	460	6			
XN1207-25	61.53	135.9	294.6	0.46	0.0573	0.0028	0.6150	0.0302	0.0781	0.0013	501	78	487	19	485	8			
XN1207-26	178.71	122.8	3581.0	0.03	0.0562	0.0017	0.3811	0.0106	0.0492	0.0007	461	70	328	8	309	4			
XN1207-27	24.12	376.6	587.1	0.64	0.0485	0.0037	0.0769	0.0059	0.0117	0.0003	121	126	75	6	75	2			
XN1207-28	9.40	17.5	1650.3	0.01	0.0519	0.0040	0.0312	0.0022	0.0048	0.0002	283	96	31	2	31	1			
XN1207-29	836.53	209.6	1647.9	0.13	0.1567	0.0045	7.4274	0.1778	0.3437	0.0052	2421	49	2164	21	1905	25			
XN1207-30	417.50	533.9	1151.8	0.46	0.0696	0.0021	1.3427	0.0416	0.1391	0.0015	917	46	864	18	840	8			
XN1207-31	391.25	503.6	1127.4	0.45	0.0639	0.0027	1.1085	0.0453	0.1258	0.0014	739	92	757	22	764	8			
XN1207-32	502.31	389.7	3574.0	0.11	0.0671	0.0018	1.0491	0.0260	0.1134	0.0013	841	58	728	13	692	7			
XN1207-33	346.36	292.1	3055.7	0.10	0.0620	0.0028	0.7134	0.0289	0.0834	0.0017	675	100	547	17	517	10			
XN1207-34	19.77	60.8	2953.7	0.02	0.0477	0.0027	0.0494	0.0028	0.0076	0.0001	82	89	49	3	49	1			
XN1207-35	1572.02	1476.2	2054.6	0.72	0.0975	0.0022	2.0506	0.0483	0.1509	0.0021	1577	24	1132	16	906	12			
XN1207-36	94.92	73.4	1219.2	0.06	0.0583	0.0018	0.6490	0.0202	0.0807	0.0010	543	46	508	12	500	6			
XN1207-37	117.23	328.7	1451.0	0.23	0.0591	0.0021	0.4212	0.0158	0.0514	0.0007	570	56	357	11	323	5			
XN1207-38	33.78	2481.8	2904.2	0.85	0.0747	0.0184	0.0195	0.0030	0.0027	0.0001	1060	267	20	3	17	1			
XN1207-39	1899.12	1301.7	2597.0	0.50	0.0982	0.0030	3.0628	0.0876	0.2262	0.0026	1590	59	1423	22	1315	14			
XN1207-40	20.05	763.5	1288.3	0.59	0.0601	0.0086	0.0317	0.0024	0.0049	0.0001	607	114	32	2	32	1			
XN1207-41	1935.42	1753.9	991.0	1.77	0.0830	0.0057	2.5341	0.1714	0.2215	0.0030	1269	139	1282	49	1290	16			
XN1207-42	253.89	655.9	1201.1	0.55	0.0604	0.0024	0.4597	0.0180	0.0554	0.0008	617	58	384	12	348	5			
XN1207-43	104.32	230.8	519.3	0.44	0.0604	0.0027	0.6247	0.0275	0.0757	0.0010	619	72	493	17	470	6			
XN1207-44	111.09	192.1	946.1	0.20	0.0616	0.0027	0.4953	0.0215	0.0584	0.0009	660	67	408	15	366	5			
XN1207-45	218.59	313.0	2223.5	0.14	0.0563	0.0015	0.5831	0.0160	0.0751	0.0008	462	41	466	10	467	5			
XN1207-46	9.31	51.1	1980.1	0.03	0.0550	0.0064	0.0256	0.0028	0.0039	0.0001	411	187	26	3	25	1			
XN1207-47	226.25	64.5	5041.6	0.01	0.0566	0.0013	0.4446	0.0095	0.0570	0.0005	476	52	373	7	357	3			
XN1207-48	269.86	413.5	2269.3	0.18	0.0581	0.0017	0.6025	0.0177	0.0749	0.0008	534	46	479	11	466	5			
XN1207-49	386.32	471.7	1626.9	0.29	0.0650	0.0016	1.0700	0.0278	0.1193	0.0015	773	33	739	14	726	9			
XN1207-50	710.97	262.6	5194.1	0.05	0.0999	0.0035	1.8633	0.0535	0.1352	0.0027	1623	67	1068	19	818	15			

续表 2

Continued Table 2

测点号	含量( ×10 <sup>-6</sup> )			Th/U	同位素比值						年龄( Ma)					
	Pb	Th	U		<sup>207</sup> Pb	1σ	<sup>207</sup> Pb	1σ	<sup>206</sup> Pb	1σ	<sup>207</sup> Pb	1σ	<sup>207</sup> Pb	1σ	<sup>206</sup> Pb	1σ
					<sup>206</sup> Pb		<sup>235</sup> U		<sup>238</sup> U		<sup>206</sup> Pb		<sup>235</sup> U		<sup>238</sup> U	
XN1207-51	29.65	452.6	524.8	0.86	0.0526	0.0039	0.0894	0.0063	0.0135	0.0004	310	111	87	6	86	2
XN1207-52	28.40	181.7	848.9	0.21	0.0489	0.0029	0.1319	0.0077	0.0196	0.0004	141	100	126	7	125	2
XN1207-53	130.35	24.5	2433.6	0.01	0.0695	0.0027	0.5520	0.0198	0.0576	0.0008	915	81	446	13	361	5
XN1207-54	230.43	303.0	2645.3	0.11	0.0561	0.0019	0.3242	0.0107	0.0419	0.0006	455	47	285	8	265	4
XN1207-55	1475.04	284.7	2263.3	0.13	0.2011	0.0049	11.2700	0.2526	0.4065	0.0037	2835	40	2546	21	2199	17
XN1207-56	224.34	316.4	2245.1	0.14	0.0558	0.0015	0.6098	0.0168	0.0785	0.0007	445	44	483	11	487	4
XN1207-57	303.53	347.9	2060.6	0.17	0.0583	0.0018	0.4624	0.0147	0.0571	0.0007	541	47	386	10	358	4
XN1207-58	182.91	468.3	604.5	0.77	0.0561	0.0027	0.5740	0.0280	0.0739	0.0011	456	82	461	18	460	6
XN1207-59	646.64	2139.0	2288.4	0.93	0.0539	0.0015	0.4536	0.0125	0.0605	0.0006	365	46	380	9	379	3
XN1207-60	206.84	505.9	620.9	0.81	0.0565	0.0024	0.6154	0.0273	0.0784	0.0011	471	74	487	17	487	6
XN1207-61	91.79	49.1	2392.1	0.02	0.0461	0.0042	0.0363	0.0028	0.0057	0.0003	–	198	36	3	37	2
XN1207-62	573.30	573.1	786.3	0.73	0.0733	0.0022	1.3409	0.0396	0.1326	0.0014	1022	43	864	17	802	8
XN1207-63	37.15	43.5	5021.3	0.01	0.0512	0.0027	0.0599	0.0033	0.0085	0.0001	252	94	59	3	54	1
XN1207-64	1062.94	540.2	846.0	0.64	0.1062	0.0035	4.2178	0.1327	0.2880	0.0027	1735	62	1677	26	1632	14
XN1207-65	470.80	389.8	1631.3	0.24	0.0701	0.0026	1.3194	0.0440	0.1364	0.0022	932	78	854	19	824	12
XN1207-66	1278.49	356.7	879.0	0.41	0.1841	0.0051	11.9514	0.2993	0.4708	0.0052	2690	46	2601	23	2487	23
XN1207-67	131.94	66.6	2380.8	0.03	0.0537	0.0021	0.2723	0.0110	0.0368	0.0007	357	58	245	9	233	4
XN1207-68	8.83	359.8	739.2	0.49	0.0461	0.0038	0.0171	0.0010	0.0027	0.0002	–	183	17	1	17	1
XN1207-69	792.05	371.9	772.5	0.48	0.1107	0.0038	4.6260	0.1471	0.3031	0.0038	1811	64	1754	27	1707	19
XN1207-70	1144.59	1190.2	733.8	1.62	0.0735	0.0023	1.7022	0.0513	0.1680	0.0019	1028	42	1009	19	1001	11
XN1207-71	182.69	182.1	275.7	0.66	0.0763	0.0030	1.6428	0.0618	0.1572	0.0023	1103	52	987	24	941	13
XN1207-72	22.34	27.6	3483.3	0.01	0.0510	0.0032	0.0586	0.0047	0.0089	0.0005	238	88	58	4	57	3
XN1207-73	1046.85	1117.0	2684.9	0.42	0.0714	0.0017	1.1514	0.0357	0.1156	0.0022	970	33	778	17	705	13
XN1207-74	95.67	18.1	2337.7	0.01	0.0547	0.0019	0.3578	0.0124	0.0481	0.0009	401	45	311	9	303	6
XN1207-75	748.92	1251.9	5135.5	0.24	0.0556	0.0013	0.5111	0.0120	0.0660	0.0006	436	37	419	8	412	3

注:同位素比值和年龄使用 Andersen (2002)方法校正

与中部拉萨地块的超钾质火山岩中的锆石捕掳晶的年龄分布不同(孙晨光等, 2008; 刘栋等, 2011; Liu *et al.*, 2013a), 学那超钾质脉岩具有更多的元古代-古生代古老锆石记录, 且锆石 U-Pb 年龄集中在四个主要的年龄范围内(<100Ma、300~400Ma、450~500Ma 以及 700~850Ma; 图 4b)。

从前两个年龄范围看, 南部拉萨地块上晚白垩纪-古近纪(100~23Ma)的岩浆活动广泛分布(Chung *et al.*, 2005; Mo *et al.*, 2008; Wen *et al.*, 2008; Ji *et al.*, 2009; Lee *et al.*, 2009; Zhu *et al.*, 2011b)。此外泥盆纪-石炭纪(400~300Ma)的岩浆活动在冈底斯岩基中也被识别出来(董昕等, 2010; Ji *et al.*, 2012)。相比之下, 除了特提斯喜马拉雅上的措美~132Ma 的辉绿岩岩墙群, 作为印度大陆北缘的喜马拉雅造山带却缺乏上述的同期岩浆活动记录(Zhu *et al.*, 2013)。这表明超钾质脉岩中晚古生代-新生代(<400Ma)的锆石记录主要来自南部拉萨地块的地壳本身。

从上述的后两个年龄范围看(450~500Ma 以及 700~850Ma), 中部拉萨地块的碎屑锆石和 S 型花岗岩的继承锆石

年龄记录表明, 拉萨地块具有 1100~1200Ma 的年龄峰值, 且缺少 800Ma 左右的年龄峰值(朱弟成等, 2011; Zhu *et al.*, 2011b), 而喜马拉雅造山带的研究则显示出明显存在 450~500Ma 和 700~850Ma 的岩浆-变质事件(Singh *et al.*, 2002; Singh and Jain, 2003; Zhu *et al.*, 2012)。同时, 大量研究表明南部拉萨地块从晚中生代到早新生代的各类岩浆岩长期显示了新生地壳的同位素组成且没有显示出存在古老地壳基底(Wen *et al.*, 2008; Chung *et al.*, 2009; Lee *et al.*, 2009; Zhu *et al.*, 2011a)。此外, Hf 同位素随时间的变化还揭示了一个重要的信息, 即从~55Ma 开始, 超钾质脉岩中的锆石  $\varepsilon_{\text{Hf}}(t)$  值从 +10~+5 迅速下降至 -10~-25 (图 5c), 进一步支持古老印度陆壳物质的加入。因此, 本文样品中的早古生代至前寒武纪的继承锆石的年龄记录, 暗示这些超钾质脉岩中存在俯冲的印度大陆地壳的物质加入。

综合以上的分析, 南部拉萨地块超钾质脉岩的锆石记录可能同时反映了南部拉萨地块与印度大陆北缘地壳这两种地壳物质的加入。无论如何, 本文在南部拉萨地块学那超钾质岩石中获得的锆石年代学和 Hf 同位素结果进一步支持

表 3 藏南学那地区超钾质岩石锆石微量元素数据

Table 3 Trace element composition of zircons from ultrapotassic rocks in Xuena area, southern Tibet

测点号	年龄 (Ma)	微量元素( ×10 <sup>-6</sup> )																			U/Yb	(Dy/Yb) <sub>N</sub>
		Ti	Y	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta		
XN1207-01	64.1	3.33	2076	7.88	n. d.	35.4	0.05	0.88	2.99	0.85	24.9	10.6	149	61.3	313	69.6	752	143	12992	3.56	1.99	0.13
XN1207-02	57.8	2.37	4633	8.79	0.04	12.1	0.10	1.31	6.43	0.85	62.2	24.6	335	132	657	138	1477	277	12250	2.12	0.77	0.15
XN1207-03	843	4.58	2624	0.71	1.09	4.14	0.41	3.53	7.99	0.41	61.2	21.0	256	83.0	336	59.9	554	90.3	11806	0.54	0.57	0.30
XN1207-04	433	5.05	3776	2.29	0.20	2.68	0.09	0.89	2.65	0.14	27.4	15.8	258	111	610	144	1591	284	15358	2.91	0.67	0.11
XN1207-05	58.0	2.49	2256	8.92	0.09	33.7	0.11	1.31	3.99	0.67	34.6	12.8	169	66.4	331	69.3	750	142	12722	2.83	1.16	0.15
XN1207-06	359	0.00	64	0.10	n. d.	5.89	0.03	0.78	0.66	0.27	3.03	0.80	6.95	2.03	7.45	1.35	14.4	2.87	6011	0.02	2.30	0.31
XN1207-07	752	5.88	1643	1.03	0.04	0.86	0.05	0.67	3.18	0.08	23.0	9.89	138	52.2	248	51.7	535	94.0	13160	1.21	1.11	0.17
XN1207-08	707	3.30	1066	2.85	6.17	26.2	1.91	10.6	5.82	0.64	22.8	7.36	94.2	34.8	160	32.7	334	58.9	9801	2.17	1.11	0.18
XN1207-09	43.0	4.45	321	1.36	0.004	0.65	n. d.	0.35	1.18	0.39	8.3	2.69	28.8	10.0	52.9	13.1	149	25.1	14661	1.37	7.52	0.13
XN1207-10	319	6.58	919	1.28	0.004	0.14	n. d.	0.11	0.31	0.07	5.7	3.85	68.0	28.7	155	41.2	513	99.1	15378	1.94	4.21	0.09
XN1207-11	335	6.52	929	1.72	0.10	1.22	0.11	1.10	2.06	0.28	11.4	4.70	73.3	29.3	153	37.4	446	84.5	13855	2.28	2.31	0.11
XN1207-12	441	7.80	1505	1.00	0.22	6.58	0.19	2.47	5.31	1.04	31.3	10.6	136	51.0	230	45.9	444	78.2	8686	0.52	0.23	0.20
XN1207-13	590	5.38	362	0.97	0.05	10.8	0.04	0.36	0.64	0.20	3.83	1.74	25.1	10.9	61.3	15.8	197	42.0	11957	1.04	1.04	0.08
XN1207-14	77.0	4.68	802	0.63	0.03	0.22	0.02	0.31	0.74	0.13	10.4	5.77	75.0	24.1	99.8	19.9	199	34.2	14526	0.68	6.29	0.25
XN1207-15	58.0	5.21	3577	5.87	0.37	55.9	0.30	4.81	13.1	4.69	84.9	27.3	314	104	425	87.5	873	156	12465	1.74	0.89	0.23
XN1207-16	19.8	0.32	776	1.05	0.03	0.75	n. d.	0.25	0.77	0.47	5.7	4.02	61.6	24.1	103	17.6	136	19.6	15016	0.90	2.92	0.29
XN1207-17	1256	5.48	1858	1.11	0.05	3.07	0.19	3.85	6.69	0.86	43.3	13.7	176	62.8	278	55.2	535	94.0	10114	1.03	0.35	0.21
XN1207-18	746	3.33	857	1.82	n. d.	21.3	0.04	0.70	2.58	0.35	16.6	5.65	73.2	28.0	131	27.7	281	50.2	11733	0.78	0.77	0.17
XN1207-19	271	4.71	767	0.46	0.06	0.23	0.01	0.00	0.38	0.03	4.93	3.42	55.6	24.6	128	32.8	394	76.2	13571	1.19	2.35	0.09
XN1207-20	21.6	3.13	560	3.18	n. d.	1.72	0.01	0.07	0.17	0.22	5.03	2.82	45.5	16.8	65.2	11.0	94.7	13.2	14899	4.88	18.7	0.31
XN1207-21	628	9.99	5403	0.93	94.8	201	23.8	101	29.5	1.48	84.6	32.7	445	159	719	141	1283	197	13238	1.03	0.81	0.23
XN1207-22	286	3.46	810	1.09	n. d.	0.51	0.003	0.25	0.38	0.06	4.50	3.13	56.3	25.5	139	36.8	434	82.4	13888	2.29	1.99	0.08
XN1207-23	18.4	1.24	423	0.50	0.002	0.55	0.03	0.11	0.53	0.21	4.13	2.11	34.5	13.8	65.7	13.7	125	19.2	14067	0.42	3.57	0.18
XN1207-24	460	6.09	2915	4.59	1.35	23.3	0.65	6.19	9.05	0.53	51.2	18.3	244	92.4	437	92.3	925	158	13066	2.97	0.73	0.17
XN1207-25	485	3.64	406	1.12	0.004	4.80	0.03	0.21	1.01	0.29	5.73	2.17	28.7	12.2	63.8	15.8	186	39.1	11407	0.62	0.54	0.10
XN1207-26	309	98.5	778	1.69	0.21	0.72	0.09	0.94	1.53	0.24	8.94	4.46	62.5	25.2	133	36.4	461	88.5	14323	2.03	2.74	0.09
XN1207-27	75.0	9.39	1419	1.57	n. d.	8.68	0.05	1.69	3.90	0.87	24.3	8.19	112	45.1	218	47.1	496	91.8	9427	0.74	0.41	0.15
XN1207-28	31.0	3.31	511	0.33	n. d.	0.14	0.03	0.00	1.39	0.14	11.5	5.07	57.2	15.5	53.5	9.13	78.7	11.6	15259	0.14	7.32	0.47
XN1207-29	1905	5.66	2465	2.28	0.06	3.60	0.12	1.15	3.16	0.10	32.8	15.0	213	78.6	351	69.6	676	114	14657	1.32	0.86	0.20
XN1207-30	840	5.43	1419	1.75	0.002	5.87	0.02	0.85	3.65	0.13	26.2	9.60	123	46.2	207	42.3	415	70.2	12820	1.29	0.97	0.19
XN1207-31	764	7.03	3105	1.33	0.03	2.67	0.09	1.56	4.86	0.15	35.0	16.7	237	94.1	469	98.2	938	155	13274	1.05	0.43	0.16
XN1207-32	692	12.6	3805	1.84	0.14	1.55	0.07	1.20	3.68	0.13	36.2	18.3	292	114	554	122	1199	197	15998	1.90	1.08	0.16
XN1207-33	517	8.42	1343	0.86	n. d.	2.23	n. d.	0.40	1.05	0.10	7.79	4.55	83.3	40.8	272	80.5	1106	249	13225	0.40	0.97	0.05
XN1207-34	48.9	11.5	3762	17.6	0.02	5.53	0.02	0.07	2.00	1.21	28.2	15.0	251	108	557	127	1384	250	16343	7.20	0.77	0.12
XN1207-35	906	22.2	2398	6.11	0.04	11.6	0.21	4.92	10.4	2.64	60.5	18.9	229	82.0	355	70.8	687	119	10067	1.75	1.05	0.22
XN1207-36	500	6.54	244	0.98	0.02	1.01	0.0041	0.25	0.38	0.15	2.5	1.00	16.5	7.33	39.8	10.0	122	26.6	12888	0.95	3.44	0.09
XN1207-37	323	9.11	2548	1.62	0.05	1.76	0.10	2.71	6.64	0.29	43.8	16.5	215	80.7	379	82.5	834	146	13359	1.16	0.61	0.17
XN1207-38	17.4	13.0	325	1.65	0.11	27.3	0.02	0.72	2.57	1.16	10.9	2.62	28.4	9.75	43.9	9.14	100	19.9	9313	1.53	9.98	0.19
XN1207-39	1315	20.9	2252	5.43	8.78	36.0	2.87	15.5	9.71	0.38	45.5	15.0	199	74.9	349	69.4	661	114	12314	3.14	1.38	0.20



续表 3  
Continued Table 3

测点号	年龄 (Ma)	微量元素( ×10 <sup>-6</sup> )																			U/Yb	(Dy/Yb) <sub>N</sub>
		Ti	Y	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta		
XN1207-40	31. 7	16. 3	487	0.90	0. 03	15. 0	0. 29	5. 37	8. 39	0. 98	29. 3	6. 71	59. 9	15. 6	58. 3	10. 1	87. 2	13. 8	11858	0. 41	5. 09	0. 45
XN1207-41	1269	17. 6	1931	3. 28	0. 39	68. 8	0. 42	6. 03	10. 3	3. 29	46. 4	14. 4	171	61. 8	279	56. 6	555	99. 3	9028	1. 12	0. 62	0. 20
XN1207-42	348	8. 36	2527	1. 99	0. 07	6. 86	0. 15	4. 36	10. 4	1. 62	61. 4	19. 7	241	82. 5	375	77. 3	781	139	10755	1. 26	0. 54	0. 20
XN1207-43	470	560	2777	1. 22	0. 003	1. 75	0. 21	2. 46	6. 69	0. 26	40. 7	16. 8	232	87. 4	414	86. 5	842	142	12403	0. 63	0. 23	0. 18
XN1207-44	366	6. 26	983	1. 24	0. 08	11. 2	0. 05	1. 06	2. 13	0. 63	15. 3	5. 78	83. 2	30. 1	141	29. 7	293	49. 6	11555	0. 87	1. 12	0. 18
XN1207-45	467	4. 21	4030	2. 52	0. 03	2. 78	0. 06	0. 77	3. 18	0. 19	30. 2	16. 6	273	120	629	147	1532	261	13204	2. 36	0. 52	0. 12
XN1207-46	25. 1	12. 7	468	0. 51	1. 51	4. 38	0. 39	2. 61	2. 87	0. 43	16. 3	5. 03	50. 6	14. 5	55. 1	11. 4	113	19. 4	14230	0. 28	6. 09	0. 29
XN1207-47	357	2. 70	1488	1. 83	0. 06	0. 81	0. 09	0. 34	0. 95	0. 74	9. 52	4. 76	90. 7	45. 1	309	97. 4	1361	283	14354	2. 29	1. 35	0. 04
XN1207-48	466	5. 55	6167	2. 51	0. 36	4. 87	0. 18	2. 13	5. 97	0. 58	56. 0	26. 9	432	179	938	214	2197	371	11995	2. 08	0. 38	0. 13
XN1207-49	726	3. 78	2138	1. 74	0. 04	2. 72	0. 05	1. 79	3. 83	0. 12	35. 6	14. 2	191	65. 9	279	57. 6	552	92. 1	13001	1. 17	1. 03	0. 22
XN1207-50	818	24. 0	1140	2. 36	0. 31	1. 47	0. 22	1. 56	2. 92	0. 67	15. 1	5. 62	83. 2	34. 1	185	44. 3	468	81. 3	13904	1. 80	3. 93	0. 12
XN1207-51	86. 0	9. 56	1421	0. 87	0. 05	13. 8	0. 21	3. 33	6. 08	1. 02	30. 4	10. 1	126	44. 8	200	40. 9	408	71. 0	10114	0. 52	0. 44	0. 20
XN1207-52	125	4. 40	509	2. 27	0. 01	9. 47	0. 02	0. 69	1. 79	0. 95	10. 5	3. 46	42. 5	15. 1	71. 6	15. 2	166	30. 8	11975	0. 60	1. 76	0. 17
XN1207-53	361	3. 61	1059	1. 60	0. 04	0. 13	0. 001	0. 26	0. 37	0. 06	5. 84	4. 23	77. 1	32. 1	177	47. 0	552	103	15335	1. 82	1. 56	0. 09
XN1207-54	265	7. 91	1089	2. 79	0. 05	7. 39	0. 07	0. 59	1. 02	0. 37	9. 55	5. 14	78. 6	33. 4	176	43. 1	493	88. 1	14036	2. 38	1. 89	0. 10
XN1207-55	2199	9. 41	833	2. 33	0. 04	10. 9	0. 09	0. 51	1. 52	0. 28	11. 3	4. 91	65. 0	24. 3	112	22. 9	232	42. 3	14421	5. 67	3. 42	0. 18
XN1207-56	487	7. 40	3925	2. 38	0. 05	3. 14	0. 03	1. 08	3. 49	0. 24	35. 3	16. 6	274	117	598	136	1408	236	13026	2. 14	0. 57	0. 13
XN1207-57	358	6. 24	964	1. 33	0. 04	3. 11	0. 12	1. 66	3. 37	0. 21	16. 6	5. 93	82. 8	30. 3	143	31. 9	346	58. 3	13794	1. 42	2. 08	0. 16
XN1207-58	460	2. 05	1266	1. 56	0. 06	8. 99	0. 16	2. 60	4. 69	1. 11	25. 0	7. 88	105	39. 2	189	42. 2	453	85. 7	10677	0. 90	0. 46	0. 15
XN1207-59	379	2. 46	1443	6. 01	4. 54	60. 4	1. 33	6. 89	3. 53	0. 89	20. 9	7. 53	104	43. 4	216	51. 6	582	110	12223	2. 45	1. 38	0. 12
XN1207-60	487	4. 61	1115	2. 45	n. d.	16. 8	0. 06	1. 44	3. 01	0. 94	19. 7	6. 71	90. 4	35. 1	174	37. 6	401	73. 5	10598	1. 07	0. 53	0. 15
XN1207-61	37. 0	12. 9	866	0. 94	0. 46	4. 42	0. 31	3. 00	3. 07	0. 73	9. 0	4. 17	64. 6	26. 0	133	31. 4	350	58. 3	14229	1. 14	2. 39	0. 12
XN1207-62	802	9. 72	2082	6. 95	0. 12	13. 7	0. 55	9. 02	13. 0	1. 12	59. 7	18. 9	211	68. 9	291	54. 7	514	88. 3	10817	4. 69	0. 53	0. 27
XN1207-63	54. 2	2. 94	1574	1. 29	0. 23	1. 18	0. 15	0. 41	1. 21	0. 28	12. 2	7. 23	121	46. 5	212	40. 4	369	62. 0	14912	2. 20	4. 79	0. 21
XN1207-64	1735	7. 00	628	1. 75	0. 02	9. 17	0. 10	1. 07	3. 54	0. 06	15. 7	4. 98	58. 2	20. 2	87. 0	17. 1	164	28. 0	10623	0. 89	1. 78	0. 23
XN1207-65	824	5. 18	1742	0. 77	0. 002	1. 28	0. 06	1. 70	5. 12	0. 08	36. 8	13. 9	168	53. 2	213	38. 8	349	55. 8	13380	0. 64	1. 64	0. 31
XN1207-66	2690	8. 11	1294	5. 79	0. 05	11. 5	0. 10	1. 77	3. 14	0. 50	22. 7	8. 28	110	42. 5	193	38. 5	378	66. 1	9506	2. 38	0. 80	0. 19
XN1207-67	233	7. 15	865	1. 16	0. 01	0. 63	0. 07	0. 27	0. 82	0. 21	4. 85	3. 39	61. 6	25. 8	146	34. 1	398	75. 3	13027	1. 42	2. 09	0. 10
XN1207-68	17. 0	4. 68	32	0. 46	n. d.	4. 33	0. 004	0. 22	n. d.	0. 10	1. 20	0. 32	3. 03	0. 98	3. 51	0. 84	10. 1	2. 04	7900	0. 25	24. 8	0. 20
XN1207-69	1811	8. 89	709	0. 89	0. 005	5. 30	0. 16	2. 46	4. 17	0. 19	19. 2	5. 81	64. 3	22. 2	99. 2	18. 6	175	30. 2	9578	0. 54	1. 51	0. 24
XN1207-70	1028	14. 0	1560	1. 70	5. 07	22. 8	1. 83	15. 2	11. 6	0. 65	50. 6	14. 0	156	50. 6	214	39. 1	349	58. 6	10313	0. 96	0. 73	0. 29
XN1207-71	941	8. 80	1230	4. 37	0. 26	9. 06	0. 17	2. 15	3. 90	0. 49	21. 2	7. 98	103	39. 7	188	36. 9	367	65. 2	10438	1. 57	0. 26	0. 18
XN1207-72	57. 0	2. 76	736	0. 54	n. d.	0. 26	n. d.	n. d.	1. 20	0. 25	10. 7	5. 59	72. 3	21. 6	80. 2	14. 5	133	21. 8	14200	0. 55	9. 10	0. 35
XN1207-73	705	10. 7	1242	1. 77	0. 06	8. 64	0. 13	1. 72	3. 86	0. 17	28. 3	10. 3	118	38. 7	163	31. 6	290	48. 5	12976	1. 29	3. 24	0. 26
XN1207-74	303	5. 70	1050	0. 82	0. 07	0. 29	0. 01	0. 15	0. 63	0. 08	6. 38	3. 92	68. 2	30. 6	169	40. 8	466	86. 7	14839	1. 59	1. 77	0. 10
XN1207-75	412	63. 7	2368	5. 33	2. 26	18. 3	1. 12	7. 24	6. 40	0. 45	31. 8	13. 1	183	73. 7	380	84. 2	899	166	14551	5. 98	2. 08	0. 13

注:Dy<sub>N</sub> 和 Yb<sub>N</sub> 采用 Boynton (1984) 标准化

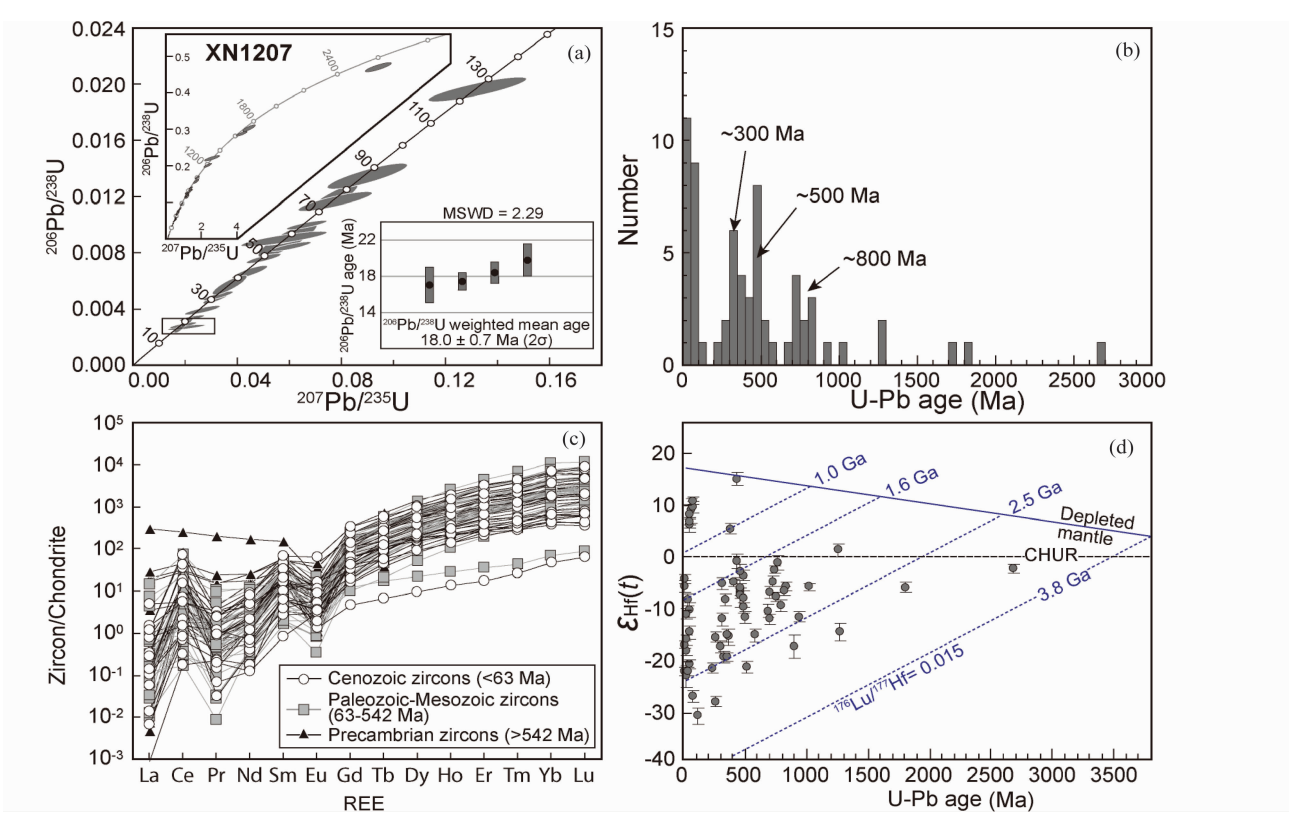


图4 藏南学那地区超钾质脉岩锆石 U-Pb 协和图 (a)、年龄直方图 (b)、REE 球粒陨石标准化图解 (c, 标准化值据 Boynton, 1984) 和 Hf 同位素 (d)  
Fig.4 U-Pb ages (a, b), REE distributin (c, normalization values after Boynton, 1984) and Hf isotopic composition (d) for zircons from ultrapotassic veins outcropped in the Xuena area, southern Tibet

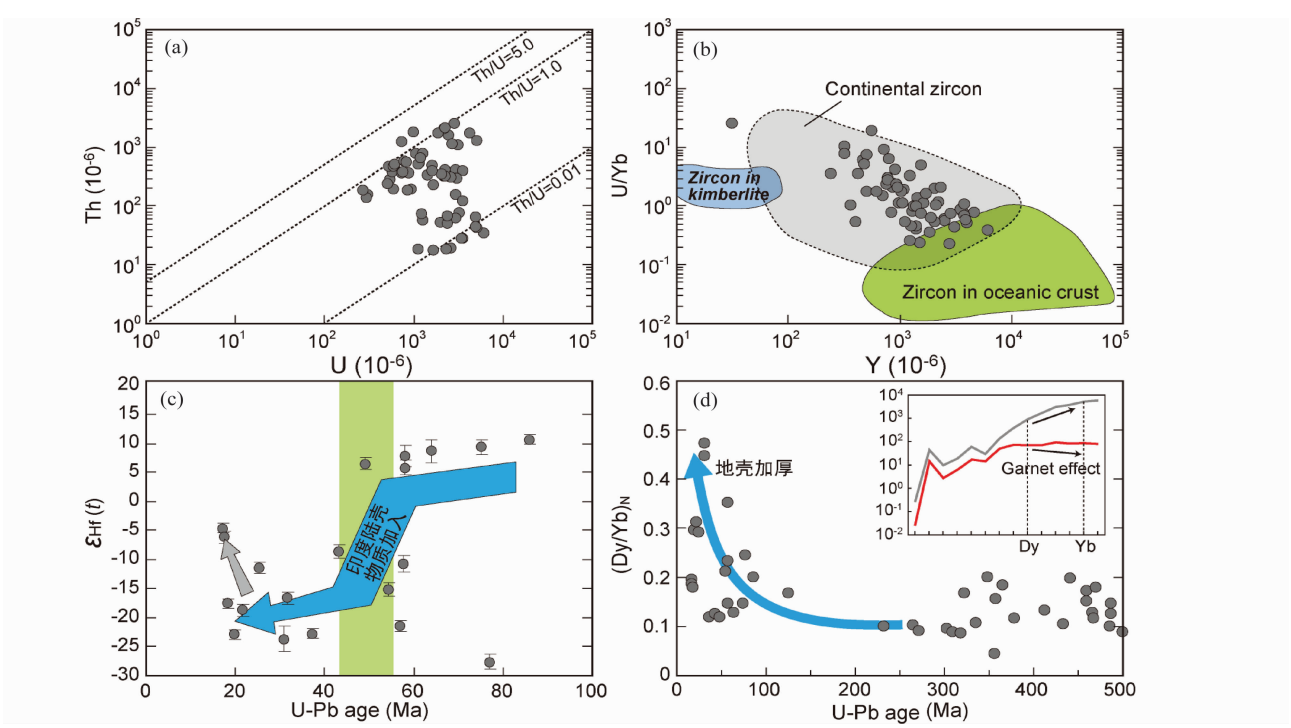


图5 藏南学那地区超钾质脉岩锆石图解  
(a)- $\text{Th}$  vs.  $\text{U}$ ; (b)- $\text{U}/\text{Yb}$  vs.  $\text{Y}$  (据 Grimes *et al.*, 2007); (c)- $\epsilon_{\text{Hf}}(t)$  vs. U-Pb age; (d)- $(\text{Dy}/\text{Yb})_{\text{N}}$  vs. U-Pb age  
Fig.5 Diagrams of  $\text{Th}$  vs.  $\text{U}$  (a),  $\text{U}/\text{Yb}$  vs.  $\text{Y}$  (b, after Grimes *et al.*, 2007),  $\epsilon_{\text{Hf}}(t)$  vs. U-Pb age (c) and  $(\text{Dy}/\text{Yb})_{\text{N}}$  vs. U-Pb age (d) for zircons from ultrapotassic veins outcropped in the Xuena area, southern Tibet

表 4 藏南学那地区超钾质岩石锆石 Hf 同位素数据

Table 4 Hafnium isotopic compositions of zircons from ultrapotassic rocks in Xuena area

测点号	年龄 (Ma)	同位素比值					$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	$t_{\text{DM}}(\text{Ma})$	$t_{\text{DM}}^{\text{c}}(\text{Ma})$	$f_{\text{Lw/Hf}}$
		$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\pm 2\sigma$	$^{176}\text{Hf}/^{177}\text{Hf}(t)$					
XN1207-01	64.1	0.086136	0.002785	0.282993	0.000066	0.282990	7.4	8.7	385	552	-0.92
XN1207-02	57.8	0.061724	0.001977	0.282447	0.000042	0.282445	-12.0	-10.8	1168	1788	-0.94
XN1207-04	433	0.101129	0.003341	0.282960	0.000037	0.282933	6.2	14.9	441	445	-0.90
XN1207-05	58.0	0.073827	0.002476	0.282973	0.000053	0.282970	6.6	7.8	412	602	-0.93
XN1207-07	752	0.062995	0.001802	0.282106	0.000027	0.282080	-24.0	-8.1	1649	2155	-0.95
XN1207-08	707	0.034705	0.001076	0.282146	0.000035	0.282132	-22.6	-7.3	1561	2070	-0.97
XN1207-09	43.0	0.010345	0.000280	0.282513	0.000031	0.282513	-9.6	-8.7	1026	1644	-0.99
XN1207-10	319	0.034864	0.001161	0.282434	0.000030	0.282427	-12.4	-5.6	1161	1660	-0.97
XN1207-11	335	0.035970	0.001116	0.282019	0.000031	0.282012	-27.1	-19.9	1740	2575	-0.97
XN1207-12	441	0.045732	0.001338	0.282482	0.000040	0.282471	-10.7	-1.3	1099	1483	-0.96
XN1207-13	590	0.024500	0.000796	0.281978	0.000035	0.281969	-28.5	-15.7	1781	2505	-0.98
XN1207-14	77.0	0.025744	0.000827	0.281956	0.000036	0.281955	-29.3	-27.6	1813	2865	-0.98
XN1207-15	58.0	0.073513	0.002386	0.282916	0.000038	0.282913	4.6	5.8	495	731	-0.93
XN1207-16	19.8	0.052631	0.001825	0.282127	0.000022	0.282127	-23.3	-22.8	1620	2522	-0.95
XN1207-17	1258	0.044225	0.001423	0.282046	0.000033	0.282013	-26.1	0.9	1716	1982	-0.96
XN1207-18	746	0.025022	0.000773	0.282244	0.000022	0.282233	-19.1	-2.9	1413	1819	-0.98
XN1207-19	271	0.035057	0.001021	0.282165	0.000030	0.282160	-21.9	-16.1	1533	2288	-0.97
XN1207-20	21.6	0.014513	0.000384	0.282242	0.000028	0.282242	-19.2	-18.7	1402	2264	-0.99
XN1207-23	18.4	0.010298	0.000263	0.282277	0.000021	0.282277	-18.0	-17.6	1349	2187	-0.99
XN1207-24	460	0.051349	0.001510	0.282301	0.000027	0.282288	-17.1	-7.3	1361	1880	-0.96
XN1207-25	485	0.021205	0.000710	0.282373	0.000027	0.282367	-14.6	-4.0	1231	1687	-0.98
XN1207-26	309	0.028976	0.000808	0.282092	0.000033	0.282087	-24.5	-17.8	1625	2424	-0.98
XN1207-27	75.0	0.070601	0.002113	0.283007	0.000036	0.283004	7.8	9.4	358	514	-0.94
XN1207-28	31.0	0.030320	0.000987	0.282097	0.000061	0.282096	-24.3	-23.7	1626	2582	-0.97
XN1207-30	840	0.033025	0.000923	0.282097	0.000024	0.282082	-24.3	-6.1	1623	2095	-0.97
XN1207-31	764	0.080558	0.002312	0.282291	0.000038	0.282258	-17.5	-1.6	1405	1753	-0.93
XN1207-32	692	0.067878	0.001841	0.282063	0.000037	0.282039	-25.5	-10.9	1711	2285	-0.95
XN1207-33	517	0.037414	0.001381	0.281854	0.000029	0.281841	-32.9	-21.9	1982	2836	-0.96
XN1207-34	49	0.045682	0.001313	0.282937	0.000029	0.282936	5.4	6.4	450	684	-0.96
XN1207-35	906	0.084306	0.002544	0.281750	0.000065	0.281706	-36.6	-17.9	2196	2884	-0.92
XN1207-36	500	0.030028	0.001085	0.282137	0.000031	0.282126	-22.9	-12.2	1575	2214	-0.97
XN1207-37	323	0.055061	0.001586	0.282237	0.000036	0.282227	-19.4	-12.5	1454	2104	-0.95
XN1207-38	17.4	0.007423	0.000228	0.282600	0.000030	0.282600	-6.5	-6.1	904	1463	-0.99
XN1207-40	31.7	0.006406	0.000139	0.282296	0.000030	0.282296	-17.3	-16.6	1319	2137	-1.00
XN1207-41	1269	0.087153	0.002747	0.281620	0.000050	0.281554	-41.2	-15.1	2394	2985	-0.92
XN1207-42	348	0.083112	0.002433	0.282335	0.000034	0.282319	-15.9	-8.7	1345	1882	-0.93
XN1207-43	470	0.101507	0.003077	0.282327	0.000034	0.282299	-16.2	-6.7	1382	1849	-0.91
XN1207-44	366	0.045070	0.001236	0.282111	0.000045	0.282102	-23.8	-16.0	1617	2354	-0.96
XN1207-45	467	0.134450	0.003970	0.282344	0.000038	0.282309	-15.6	-6.4	1392	1830	-0.88
XN1207-46	25.1	0.012033	0.000285	0.282444	0.000027	0.282444	-12.1	-11.5	1121	1810	-0.99
XN1207-47	357	0.086207	0.003106	0.282138	0.000034	0.282117	-22.9	-15.7	1662	2327	-0.91
XN1207-48	466	0.149811	0.004277	0.282307	0.000062	0.282269	-16.9	-7.9	1461	1919	-0.87
XN1207-49	726	0.031590	0.000850	0.282191	0.000029	0.282179	-21.0	-5.2	1490	1953	-0.97
XN1207-51	86.0	0.030818	0.000890	0.283033	0.000023	0.283032	8.8	10.6	308	443	-0.97
XN1207-52	125	0.022920	0.000715	0.281817	0.000045	0.281816	-34.2	-31.5	1999	3143	-0.98
XN1207-54	265	0.047624	0.001427	0.281814	0.000029	0.281807	-34.3	-28.7	2041	3072	-0.96
XN1207-56	487	0.105590	0.003079	0.282266	0.000043	0.282238	-18.3	-8.5	1471	1974	-0.91
XN1207-57	358	0.035044	0.000915	0.282002	0.000024	0.281996	-27.7	-20.0	1754	2595	-0.97
XN1207-58	460	0.036116	0.001214	0.282417	0.000034	0.282406	-13.0	-3.2	1187	1616	-0.96
XN1207-59	379	0.056166	0.001858	0.282707	0.000025	0.282694	-2.8	5.2	790	1022	-0.94
XN1207-60	487	0.052381	0.001694	0.282203	0.000030	0.282188	-20.6	-10.3	1506	2086	-0.95

续表 4  
Continued Table 4

测点号	年龄 (Ma)	同位素比值					$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	$t_{\text{DM}}(\text{Ma})$	$t_{\text{DM}}^{\text{C}}(\text{Ma})$	$f_{\text{Lu/Hf}}$
		$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\pm 2\sigma$	$^{176}\text{Hf}/^{177}\text{Hf}(t)$					
XN1207-61	37.0	0.045782	0.001348	0.282120	0.000023	0.282119	-23.5	-22.7	1609	2527	-0.96
XN1207-62	802	0.049291	0.001372	0.282022	0.000034	0.282001	-27.0	-9.8	1748	2300	-0.96
XN1207-63	54.2	0.021144	0.000602	0.282324	0.000034	0.282323	-16.3	-15.1	1297	2062	-0.98
XN1207-65	824	0.033678	0.000973	0.282081	0.000026	0.282066	-24.9	-7.0	1648	2142	-0.97
XN1207-66	2690	0.061459	0.001726	0.281069	0.000026	0.280980	-60.7	-2.6	3094	3323	-0.95
XN1207-67	233	0.045294	0.001367	0.282019	0.000029	0.282013	-27.1	-22.1	1751	2636	-0.96
XN1207-68	17.0	0.002007	0.000058	0.282644	0.000026	0.282644	-5.0	-4.6	840	1365	-1.00
XN1207-69	1811	0.027277	0.000737	0.281477	0.000029	0.281452	-46.2	-6.3	2464	2862	-0.98
XN1207-70	1028	0.033380	0.000935	0.281975	0.000023	0.281957	-28.6	-6.3	1792	2251	-0.97
XN1207-71	941	0.042050	0.001213	0.281871	0.000026	0.281849	-32.3	-12.1	1951	2546	-0.96
XN1207-72	57.0	0.027778	0.000824	0.282146	0.000027	0.282145	-22.6	-21.4	1551	2456	-0.98
XN1207-73	705	0.019626	0.000543	0.281992	0.000027	0.281985	-28.0	-12.6	1751	2398	-0.98
XN1207-74	303	0.044363	0.001494	0.281308	0.000028	0.281300	-52.2	-45.8	2747	4159	-0.96
XN1207-75	412	0.060322	0.001798	0.282388	0.000022	0.282374	-14.0	-5.4	1247	1718	-0.95

注:  $\varepsilon_{\text{Hf}}(0) = \left[ \frac{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{Sample}}}{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}}} - 1 \right] \times 10^4$ ;  $\varepsilon_{\text{Hf}}(t) = \left[ \frac{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{Sample}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{Sample}} \times (e^{\lambda t} - 1)}{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} \times (e^{\lambda t} - 1)} - 1 \right] \times 10^4$ ;  
 $t_{\text{DM}} = 1/\lambda \times \ln \left\{ 1 + \frac{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{Sample}} - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}}{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{Sample}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}} \right\}$ ;  $t_{\text{DM}}^{\text{C}} = t_{\text{DM}} - (t_{\text{DM}} - t) \times \frac{(f_{\text{MC}} - f_{\text{Sample}})}{(f_{\text{MC}} - f_{\text{DM}})}$ ;  $f_{\text{sample}} = \frac{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{Sample}}}{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}} - 1$ ;  
 $f_{\text{MC}} = \frac{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{MC}}}{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}} - 1$ ;  $f_{\text{DM}} = \frac{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}}{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}} - 1$ .  $\lambda = 1.867 \times 10^{-11} \text{ yr}^{-1}$  (Söderlund *et al.*, 2004);  $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} = 0.0336$ ,  
 $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}} = 0.282785$  (Bouvier *et al.*, 2008);  $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$ ,  $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}} = 0.28325$ ,  $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{MC}} = 0.015$   
(Griffin *et al.*, 2000, 2002).  $t$  为锆石结晶年龄, 对于小于 1000Ma 的岩浆锆石, 采用  $^{206}\text{Pb}/^{238}\text{U}$  年龄, 对大于 1000Ma 的锆石, 采用  $^{207}\text{Pb}/^{206}\text{Pb}$  年龄

印度大陆北缘成熟的地壳物质至少已经俯冲到了南部拉萨地块之下, 且参与到了碰撞后岩浆作用中。

5 结论

4.2 超钾质脉岩锆石示踪地壳加厚

对超钾质岩石成因的研究结果表明, 加厚下地壳物质对于拉萨地块超钾质岩石的形成与演化具有重要作用 (Liu *et al.*, 2013a, b)。相比于应用石榴子石相地幔橄辉岩来解释重稀土亏损的地球化学特征, 榴辉岩相下地壳物质的加入则能更好地解释上述超钾质岩石的“石榴子石”特征以及其他相关的地球化学性质 (Liu *et al.*, 2013b)。对中部拉萨地块的超钾质火山岩中的锆石捕虏晶的研究表明, 这些锆石记录了拉萨地块地壳主要的壳-幔相互作用所引发的岩浆热事件以及印度-欧亚大陆碰撞造成的地壳显著加厚 (Liu *et al.*, 2013a)。在岩浆源区存在大量石榴子石的情况下, 岩浆中重稀土 (HREE) 的含量相对缺乏, 导致结晶出的锆石具有平坦的 HREE 配分模式, 即具有高的  $(\text{Dy}/\text{Yb})_{\text{N}}$  比值。而本文超钾质脉岩中的锆石从大约 55Ma 以来展现出逐渐升高的  $(\text{Dy}/\text{Yb})_{\text{N}}$  比值 (图 5d), 暗示着陆陆碰撞造成的地壳加厚过程被南部拉萨地块上的超钾质脉岩新生代锆石所记录下来。

本文通过对南部拉萨地块学那地区超钾质脉岩中的锆石 U-Pb 年代学、微量元素和 Hf 同位素分析, 获得如下结论:  
(1) 从超钾质岩石中识别出大量具有喷发前年龄的锆石颗粒, 年龄范围从 2690Ma 到 17Ma。锆石高 U/Yb 比值、低 Y 含量的特征表明这些锆石起源于大陆地壳而非俯冲洋壳。  
(2) 通过对比南部拉萨地块和喜马拉雅造山带岩浆活动的定年结果发现, 晚古生代-新生代 ( $<400\text{Ma}$ ) 的锆石捕虏晶可能起源于拉萨地块, 而 450 ~ 500Ma 以及 700 ~ 850Ma 的古老锆石颗粒则可能来源于俯冲的印度大陆古老地壳。加上锆石  $\varepsilon_{\text{Hf}}(t)$  值从 ~55Ma 开始迅速下降, 这些证据表明在南部拉萨地块的超钾质岩浆演化过程中同时存在拉萨地块地壳物质和俯冲的印度大陆地壳物质的加入。  
(3) 从 ~55Ma 以来, 超钾质脉岩中的锆石颗粒的  $(\text{Dy}/\text{Yb})_{\text{N}}$  展现出逐渐升高, 暗示着南部拉萨地块的地壳加厚过程。

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